Final Report on AOARD contract FA2386-10-1-4090, "Laser cooling with ultrafast pulse trains"

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Submitted 8 August 2011

Overview

The goal of this contract was to investigate a novel laser-cooling technique that uses femtosecond lasers to extend the range of ultracold atomic species. This contract continued the previous AOARD contract FA2386-09-1-4015 of the same name.

In this period, the development of this project led to several immediate opportunities for high-impact experiments that were only tangentially related to the contract goals. At the same time, we were prevented from carrying out our original program by a failure of the crucial 1030 nm optical amplifier, which was not repaired by the vendor for 9 months.

Discussions with AFOSR Atomic and Molecular Physics Program Manager Tatjana Curcic resulted in a decision to pursue the new opportunities, crediting AOARD/AFOSR for the support of the experiments through this contract. The highly productive outcomes of these experiments are detailed below.

Benchmarking attosecond physics with atomic hydrogen

The high-purity atomic hydrogen beam constructed under previous AFOSR contracts, in combination with the laser system of the Australian Attosecond Science Facility (directed by the PI), presented us with a unique opportunity to benchmark strong-field attosecond physics. The interaction of intense few-cycle infrared laser pulses with matter is the fundamental process driving attosecond science, the study of phenomena with duration below 10^{-15} second. Few-cycle laser pulses have been used to reveal and control the structure and dynamics of atom, molecules and solids. The physical interpretation of such experiments relies on the accurate simulation of the complex, highly nonlinear material dynamics during the few-cycle laser pulse. Future progress in attosecond science therefore depends on a thorough understanding of the few-cycle laser interaction.

We are the only experimental research group currently investigating attosecond dynamics of atomic hydrogen, the only species for which *ab initio* simulations can be conducted. We have achieved unprecedented agreement between *ab initio* theory and experiment in this field by investigating ionisation of atomic hydrogen with few-cycle pulses [1]. Figure 1 demonstrates the excellent agreement between *ab initio* theory and experiment. Remarkably, only two global fit parameters are needed to obtain agreement at the 10% level over >250 data points.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **09 AUG 2011**	2. REPORT TYPE	3. DATES COVERED
4. TITLE AND SUBTITLE **Laser Cooling with Ultrafast Pulse Trains**		5a. CONTRACT NUMBER **FA23861014090**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Dave Kielpinski**		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Griffith University,Nathan QLD,Brisbane 4111,Australia,AU,4111**		8. PERFORMING ORGANIZATION REPORT NUMBER **N/A**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of this contract was to investigate a novel laser-cooling technique that uses femtosecond lasers to extend the range of ultracold atomic species. This contract continued the previous AOARD contract FA2386-09-1-4015 of the same name. In this period, the development of this project led to several immediate opportunities for high-impact experiments that were only tangentially related to the contract goals. At the same time, we were prevented from carrying out our original program by a failure of the crucial 1030 nm optical amplifier, which was not repaired by the vendor for 9 months. Discussions with AFOSR Atomic and Molecular Physics Program Manager Tatjana Curcic resulted in a decision to pursue the new opportunities, crediting AOARD/AFOSR for the support of the experiments through this contract. The highly productive outcomes of these experiments are detailed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**5**	

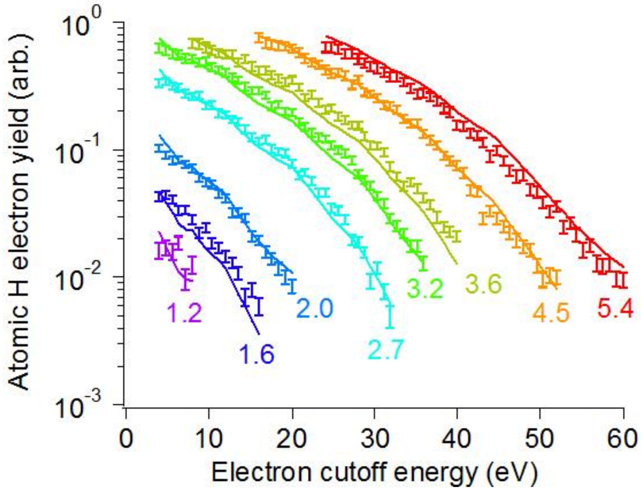

Figure 1. Experimental data (dots) versus theoretical predictions (solid line) for the direct integration of the TDSE (a) and the SFA (b). Experimental data agrees quantitatively with TDSE calculations at the 10\% level. The laser intensity range is 1.2 to 5.4×10^{14} W/cm^2 and is indicated below the corresponding data run.

Most recently, we have observed the effect of carrier-envelope phase (CEP) on the photoelectron yield from atomic hydrogen (Fig. 2a). We have made a systematic study of the electron energy and laser intensity dependence of the CEP modulation depth and relative phase offset (Fig. 2b). We are now attempting to reconcile the CEP dependence of photoelectron yield from hydrogen with *ab initio* theory. If agreement is achieved, these measurements would constitute the first theoretically calculable CEP meter. We will continue by comparing the CEP effect on H with the CEP effect on gases commonly used for CEP metering, e.g., Ar and Xe. Those measurements can serve to calibrate CEP meters in other labs with respect to *ab initio* theory.

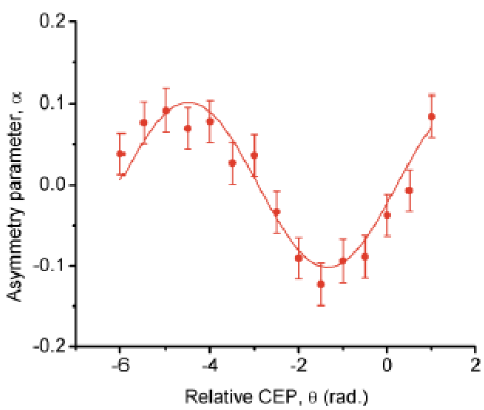

Figure 2a. Typical asymmetry data versus the relative value of the CEP. The data have been fit with a sine curve with two fit parameters (Eq. 1) which is shown as a solid line.

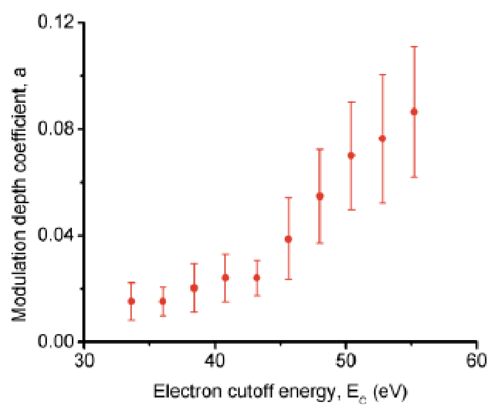

Figure 2b. The experimentally determined atomic H modulation depth co-efficient, *a*, as a function of the electron cutoff energy for a laser intensity of ~5.3 x 10^{14} W/cm^2.

Record-breaking atomic imaging resolution and first absorption imaging

The Fresnel lens imaging system [1], constructed under previous AFOSR contracts to increase our fluorescence collection efficiency for two-photon spectroscopy, was used to obtain both record-breaking spatial resolution in fluorescence imaging and the first ever absorption images of a single atom.

High-resolution imaging of trapped ions is made possible by the high numerical aperture of the Fresnel lens (NA = 0.64). The Fresnel lens forms a nominally aberration-free image when the ion is positioned on the optic axis with a ion-lens distance equal to the focal length. However, the image resolution is extremely sensitive to the exact ion position and degrades substantially when the ion is offset by only a few microns from the nominal position. Near the nominal position, we obtained ion images of 440 nm FWHM resolution (Fig. 3, left). These are the highest-resolution images ever obtained for a single atom, and the resolution is comparable to the transition wavelength of 370 nm. The resolution is only somewhat higher than the numerical-aperture-limited resolution of 300 nm FWHM.

In the absorption experiments, a trapped ion sitting in the laser beam scatters photons out of the beam and the shadow is reimaged by the phase Fresnel lens (Fig. 3, right). The high resolution of the Fresnel lens enabled us to obtain as much as 3% absorption contrast at the center of the image. The dependence of the absorption signal on laser frequency and power closely followed quantum-mechanical predictions. The absorption signal can be much stronger than the fluorescence signal in an equivalent situation, providing an improved technique for detecting single-atom quantum states. Theoretically, the residual light transmitted past the ion is entangled with the ion internal state. This phenomenon could be employed in new protocols for quantum communication.

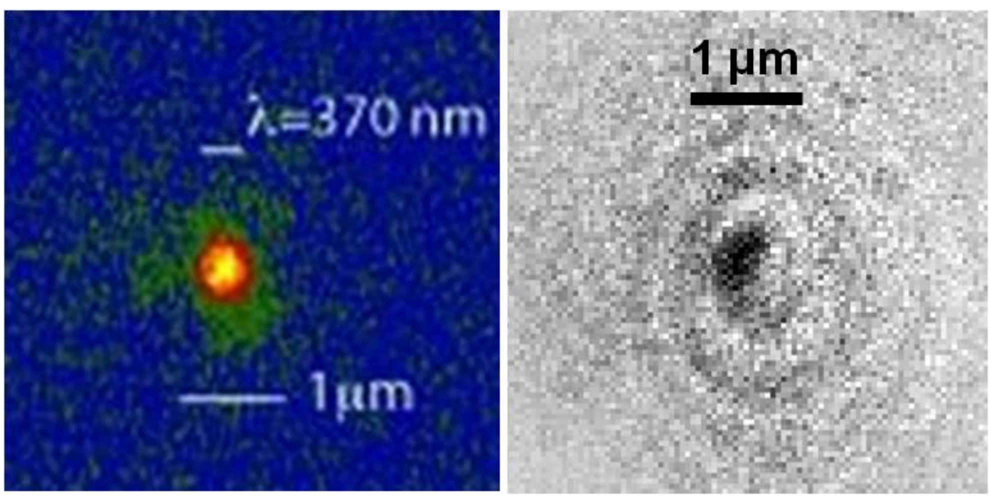

Figure 3. Left: Wavelength-scale fluorescence imaging of a single ion. The imaging resolution is the best ever obtained for an isolated atom [2]. Right: Absorption imaging of a single ion.

We used our high-resolution imaging capability to resolve the residual motion of ions at the nanometer scale and perform thermometry of the ions at the millikelvin scale [5]. Our temperature measurements have an accuracy of 5 mK, about a factor of 20 better than those typically obtained through spectroscopic measurements in this range. Since our technique does not require sweeping the laser frequency, we can observe the effect of laser cooling on the ion equilibrium temperature (Fig. 4).

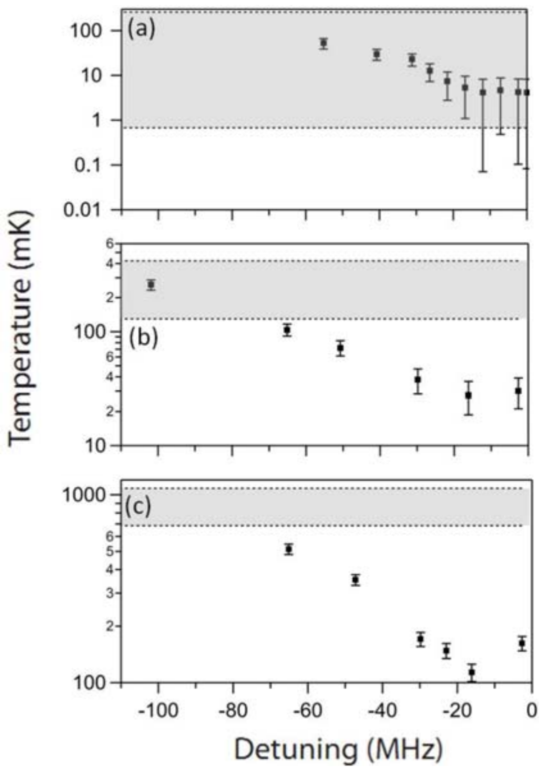

Figure 4. Ion temperature dependence on cooling laser detuning for three different externally applied heating rates, showing the change in temperature from laser cooling dynamics. Both spectroscopic and imaging temperatures for (a) no, (b) low, and (c) high external heating are shown. The uncertainty in the imaging temperature is dominated by the systematic uncertainty in the correction for ion spatial extent by the imaging resolution. The spectroscopic temperature 1σ uncertainty band for each of the three external heating rates is shown as the gray band with the upper and lower bound depicted as a dashed line.

Journal publications relating to this contract:

1. EW Streed, BG Norton, A Jechow, TJ Weinhold, and D Kielpinski, "Imaging trapped ions with a microfabricated lens for quantum information processing," *Phys Rev Lett* **106**, 010502 (2011).
2. A Jechow, EW Streed, BG Norton, MJ Petrasiunas, and D Kielpinski, "Wavelength-scale imaging of trapped ions using a phase Fresnel lens," *Opt Lett* **36**, 1371 (2011).
3. MG Pullen, WC Wallace, DE Laban, AJ Palmer, GF Hanne, AN Grum-Grzhimailo, B Abeln, K Bartschat, D Weflen, I Ivanov, A Kheifets, HM Quiney, IV Litvinyuk, RT Sang, and D Kielpinski, "Experimental few-cycle ionization of atomic hydrogen," accepted to *Opt Lett* (2011).
4. BG Norton, EW Streed, MJ Petrasiunas, A Jechow, and D Kielpinski, "Millikelvin spatial thermometry of trapped ions," arXiv:1106:1708v1 (2011).

Conference presentations relating to this contract:

5. EW Streed, BG Norton, TJ Weinhold, and D Kielpinski, "Efficient ion-photon coupling with phase Fresnel lenses," oral presentation M1.00085, 41st Annual Meeting of the American

Physical Society Division of Atomic, Molecular and Optical Physics, Houston, TX, 26-29 May 2010.

6. D Kielpinski, MG Pullen, WC Wallace, DE Laban, AJ Palmer, GF Hanne, AN Grum-Grzhimailo, B Abeln, K Bartschat, I Ivanov, A Kheifets, HM Quiney, IV Litvinyuk, RT Sang, and D Kielpinski, “Above threshold ionisation of atomic hydrogen using few-cycle pulses,” oral presentation X3.00002, 41st Annual Meeting of the American Physical Society Division of Atomic, Molecular and Optical Physics, Houston, TX, 26-29 May 2010.
7. EW Streed, BG Norton, A Jechow, TJ Weinhold, and D Kielpinski, “Scalable imaging of trapped ions,” poster presentation, International Conference on Atomic Physics, Cairns, Australia, 25-30 July 2010.
8. MG Pullen, WC Wallace, DE Laban, AJ Palmer, GF Hanne, AN Grum-Grzhimailo, B Abeln, K Bartschat, I Ivanov, A Kheifets, HM Quiney, IV Litvinyuk, RT Sang, and D Kielpinski, “Above threshold ionisation of atomic hydrogen using few-cycle pulses,” poster presentation, International Conference on Atomic Physics, Cairns, Australia, 25-30 July 2010.
9. BG Norton, EW Streed, A Jechow, TJ Weinhold, and D Kielpinski, “Phase Fresnel lenses for large scale trapped ion quantum computing,” poster presentation, Australian Institute of Physics Congress, Melbourne, 5 – 9 Dec 2010.
10. EW Streed, BG Norton, A Jechow, TJ Weinhold, and D Kielpinski, “Imaging trapped ions with a microfabricated lens for quantum information processing,” oral presentation, Australian Institute of Physics Congress, Melbourne, 5 – 9 Dec 2010.
11. B. Norton, E. Streed, A. Jechow, M. Petrasiunas, and D. Kielpinski, “Imaging the temperature of trapped ions,” oral presentation EC3.3, 2011 Conference on Lasers and Electro-Optics Europe and 12th European Quantum Electronics Conference, Munich, 22-26 May 2011.
12. A. Jechow, E. Streed, B. Norton, and D. Kielpinski, “Imaging of trapped ions with wavelength-scale resolution using a microfabricated optic,” poster presentation ED.P.8, 2011 Conference on Lasers and Electro-Optics Europe and 12th European Quantum Electronics Conference, Munich, 22-26 May 2011.